



# ***In-Situ Resource Utilization (ISRU) for Human Mars Exploration***

*Presentation to  
Mars Robotic & Human Exploration Strategic Roadmap Team  
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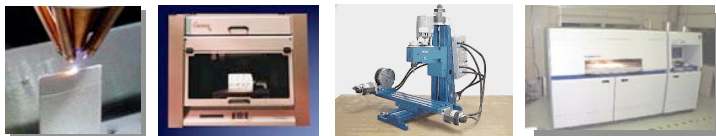


# Uses of Space Resources for Robotic & Human Exploration



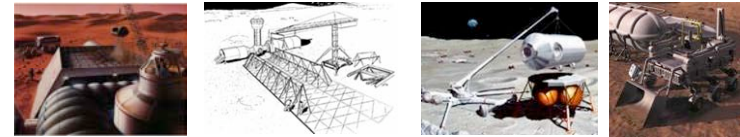
## Mission Consumable Production

- **Propellants for Lander/Ascent Vehicles, Surface Hoppers, & Aerial Vehicles**
- **Fuel cell reagents for mobile** (rovers, EVA) & stationary backup power
- **Life support consumables** (oxygen, water, buffer gases)
  - Gases for science equipment and drilling
  - Bio-support products (soil, fertilizers, etc.)
  - Feedstock for in-situ manufacturing & surface construction



## Manufacturing w/ Space Resources

- **Spare parts manufacturing**
  - Locally integrated systems & components (especially for increasing resource processing capabilities)
  - High-mass, simple items (chairs, tables, chaises, etc.)



## Surface Construction

- **Radiation shielding for habitat & nuclear reactors from in-situ resources or products** (Berms, bricks, & plates; water; hydrocarbons)
- **Landing pad clearance**, site preparation, roads, etc.
  - Shielding from micro-meteoroid and landing/ascent plume debris
  - Habitat and equipment protection



## Space Utilities & Power

- **Storage & distribution of mission consumables**
  - Thermal energy storage & use
  - Solar energy (PV, concentrators, rectennas)
- **Chemical energy (fuel cells, combustion, catalytic reactors, etc.)**



# Space Resource Utilization is Critical for Affordable, Flexible, & Sustainable Exploration



## Mass Reduction

- Reduces Earth to orbit mass by 20 to 45% for Mars missions
- 3.5:1 to 4:1 mass savings leverage from Moon/Mars surface back to Low Earth Orbit,

## Cost Reduction

- Reduces number and size of Earth launch vehicles
- Allows reuse of transportation assets
- Minimizes DDT&E cost



## Space Resource Utilization

## Risk Reduction & Flexibility



- Reduces dependence on Earth supplied logistics
- Use of common hardware & mission consumables enables increased flexibility
- In-situ fabrication of spare parts enables sustainability and self-sufficiency
- ISRU can provide dissimilar redundancy
- Radiation & Plume Shielding

## Enables Space Commercialization

- Develops material handling and processing technologies
- Provides infrastructure to support space commercialization
- Propellant/consumable depots at Earth-Moon L1 & Surface for Human exploration & commercial activities

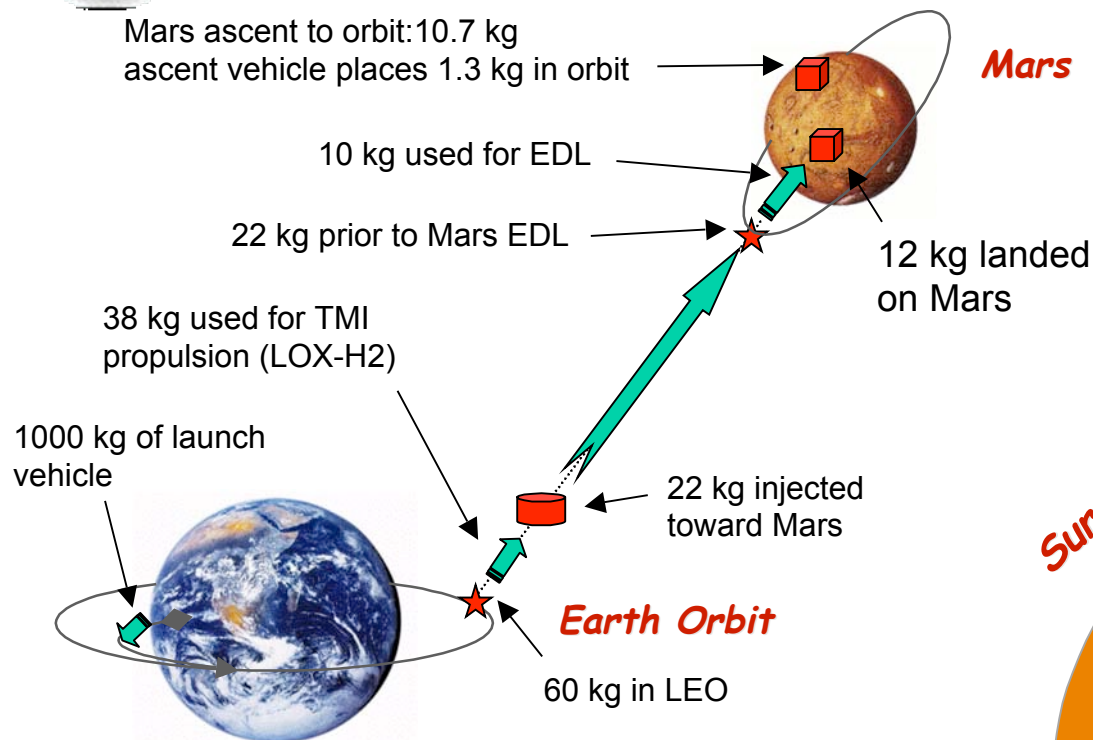
## Expands Human Presence

- Increase Surface Mobility & extends missions
- Habitat & infrastructure construction
- Propellants, life support, power, etc.
- Substitutes sustainable infrastructure cargo for propellant & consumable mass

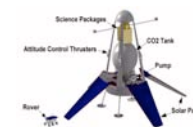
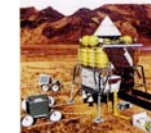




# ISRU Enables Affordable Transportation & Sustainable Surface Exploration



## Lander & Hopper Propellant Resupply & Servicing for Reuse



## Surface Exploration



Common ISRU-provided consumables for Propulsion, EVA & Habitat Life Support, and EVA Suit & Rover Power

Shielding for Radiation & Dust/Plume Protection



- >3.5:1 to 5:1 mass savings leverage from Mars surface back to Low Earth Orbit
- >80% of landed mass is propellant for ascent vehicle

- ✓ **Power-rich environment enables new science, capabilities, and relaxed power constraints**
- ✓ **Modular hardware for reduced logistics, higher reliability, and increased flexibility & safety**
- ✓ **Production of common mission consumables increases mission effectiveness, sustainability, & provides functional redundancy to minimize risk**
- ✓ **Infrastructure is reusable and expandable from simple robotic lander to full human presence**



# NASA Vision & Exploration Challenges



To Meet NASA's Mission and to meet the challenge "to explore the universe and search for life" robotic and human exploration must be **Sustainable, Affordable, Flexible, Beneficial, and Safe**

Strategic Challenges	How ISRU Meets Challenge
<b>Margins &amp; Redundancy</b>	Use of common technologies/hardware and mission consumables enables <b>swapping/cross use</b>
	See ASARA
<b>Reusability</b>	Production of mission consumables (propellants, fuel cell reagents, science gases, etc.) enables <b>reuse</b> of typical single use assets
<b>Modularity</b>	ISRU utilizes common technologies/hardware with life support, fuel cell power, and propulsion systems
<b>As Safe As Reasonably Achievable</b>	Use of <b>functional/dissimilar redundancy</b> for mission critical systems (such as life support) increases mission safety
	ISRU can <b>eliminate aborts</b> which may occur without capabilities: life support, power, spare parts, etc.
	Use of in-situ materials for radiation shield enable <b>lower levels of radiation exposure</b> compared to Earth provided shielding
<b>Robotic Networks</b>	ISRU incorporates robotic networks to enable ISRU capabilities before human occupation
<b>Affordable Logistics Pre-Positioning</b>	ISRU enables <b>large mass leveraging</b> of pre-positioned hardware into usable mission products and consumables (space parts, propellants, life support gases, etc.)
<b>Energy Rich Systems &amp; Missions</b>	Regeneration of fuel cell reagents and common mission consumables and hardware enables <b>power-rich surface elements</b> , such as EVA suits, robotic assistants, and rovers, without the cost/overhead associated with multiple nuclear assets (RTGs)
<b>Access to Surface Targets</b>	Production and regeneration of propellants and fuel cell reagents enables transport rovers and robotic and human surface hoppers at a <b>fraction of the cost</b> compared to dedicated missions launched from Earth
<b>Space Resource Utilization</b>	All of above



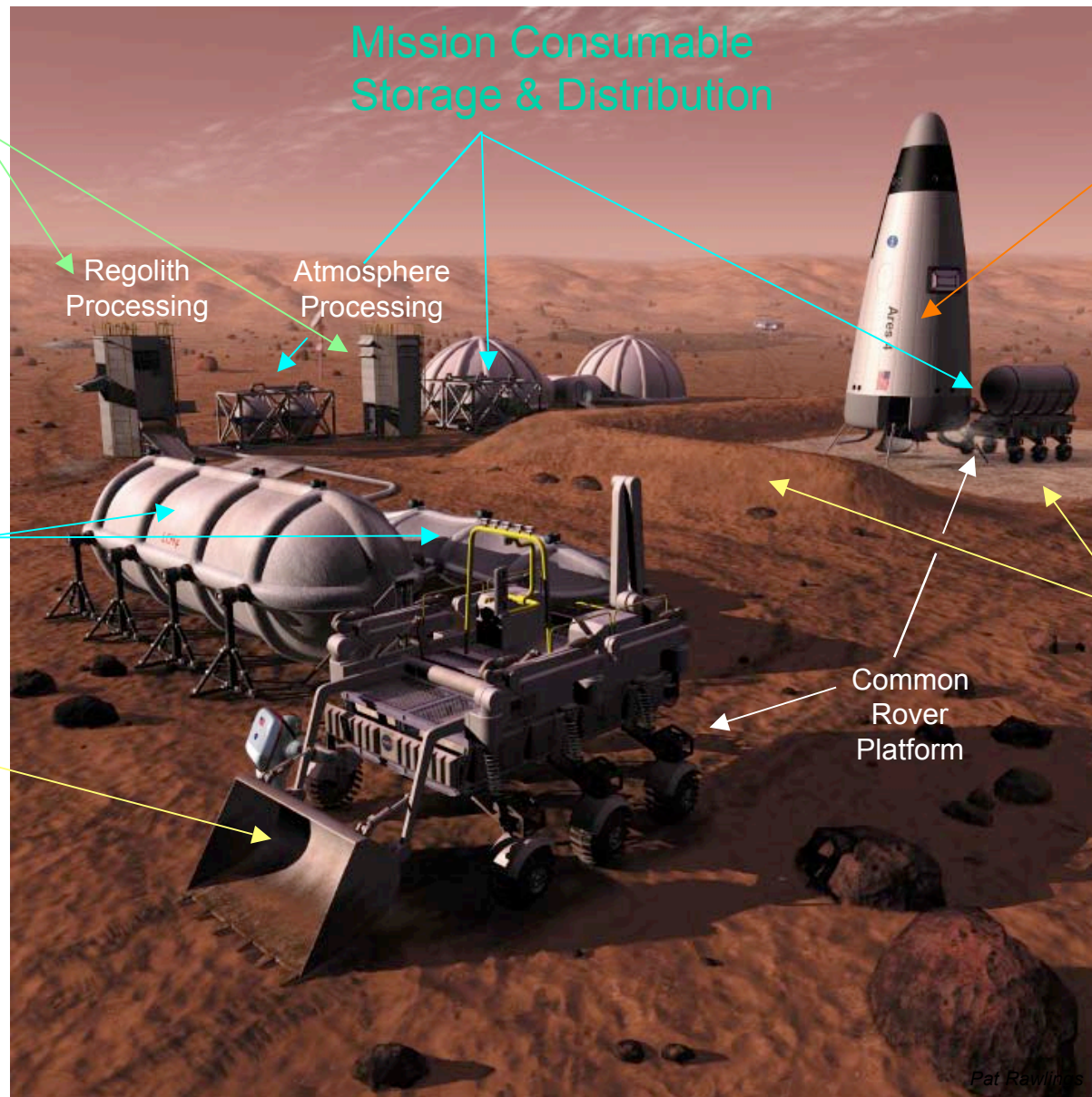
# Example Mars Base With ISRU Capability



Resource  
Processing  
Plants

Collapsible/  
Inflatable  
Cryogenic  
Tanks

Multi-use  
Construction/  
Excavator:  
resources,  
berms, nuclear  
power plant  
placement, etc.



Reusable  
lander/ascent  
vehicle or  
surface  
hopper fueled  
with in-situ  
propellants

Landing pad  
& plume  
exhaust  
berm

Common  
Rover  
Platform

Pat Rawlings



# Space Resource Utilization Dependencies



## Architecture dependant:

- Long stay vs short stay (*mission consumable mass increases with stay time*)
- Pre-deploy vs all in one mission (*pre-deploy allows longer production times but requires precision landing*)
- Multiple mission to same destination vs single missions (*multiple missions enables gradual infrastructure and production rate build up*)
- High orbit vs low orbit rendezvous (*increase in Delta-V increases benefit of in-situ produced propellant*)
- Reuse vs single mission (*reuse allows for single stage vs two stage landers and lower cost propellant depots at E-M L1*)

## Customer dependant:

- ISRU is only viable if use is designed into subsystems that utilize the products (*propellants, radiation shielding, energy storage, surface equipment, spare parts, etc.*)

## Time phased:

- Early missions must require minimum infrastructure and provide the biggest mass/cost leverage (*mission consumables have biggest impact*)
- Surface construction and manufacturing will start with simple/high leverage products and expand to greater self-sufficiency capability
- ISRU is evolutionary and needs to build on lessons learned from previous work and show clear benefit metrics



# State-of-Art of Mars ISRU



## Atmospheric Resource Processing

### Strengths

- Significant research performed on several methods of atmospheric collection and separation and processing into oxygen and fuel
- 1<sup>st</sup> generation subsystems and systems built and tested for several system concepts; 2<sup>nd</sup> generation hardware built but not tested
- One short duration system test performed under simulated Mars surface conditions
- ISRU Experiment (MIP) flight hardware build and certified for 2001 Mars Surveyor Lander (*lander mission cancelled*)
- Extramural proposal for Micro-channel Chemical/Thermal Processing awarded recently to Battelle/PNNL

### Weaknesses

- Further technology development required to lower mass and power requirements
- Some technologies which might be critical are still immature (i.e. CO<sub>2</sub> electrolysis)



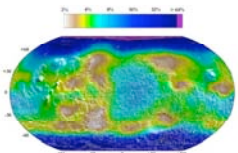
## Regolith Resource Processing

### Strengths

- Surface material characteristics studied from Mars robotic landers and rovers
- Water identified globally
- Lunar regolith excavation and thermal processing techniques can be utilized for Mars

### Weaknesses

- Form and concentration of water at locations on Mars requires further assessment
- No work currently funded for Mars regolith processing





# Past Mars ISRU Development Activities



## ISRU Technology Development

- Mars atmosphere adsorption pump collection (JPL, ARC, LMA, JSC, PNNL)
- Mars atmosphere solidification pump collection (LMA, SBIR)
- Volatile extraction from lunar soil (JSC/CSM)
- Zirconia CO<sub>2</sub> Electrolysis (Univ. of Arizona, Allied Signal, Old Dominion, SBIR)
- Water Electrolysis/Decomposition (JSC, LMA, SBIR)
- Reverse Water Gas Shift (SBIRs, KSC)
- Methane reformer (JPL, SBIR)
- Hydrocarbon fuel development (SBIRs, JSC)
- Microchannel Chemical/Thermal System Technology for ISRU (PNNL, SBIR)
- Surface cryogenic liquefaction and storage (JSC, NIST, SBIRs, LMA)
- Mars regolith acid reduction for oxygen, metals, & silicon (SBIR)

## ISRU Subsystem & System Development & Ground Testing

- CO<sub>2</sub> collection and storage subsystems tested
- 1<sup>st</sup> Generation Sabatier/Water Electrolysis (SWE) breadboard under ambient & Mars environment testing
- 1<sup>st</sup> Generation Reverse Water Gas Shift with and w/o Fuel production
- 2<sup>nd</sup> Gen SWE system breadboard - designed and subsystems built

## ISRU Flight Demonstrations

- Mars ISPP Precursor (MIP) flight demo manifested on 2001 Mars Surveyor Lander
  - Flight hardware certified and placed in Bonded Storage at JSC



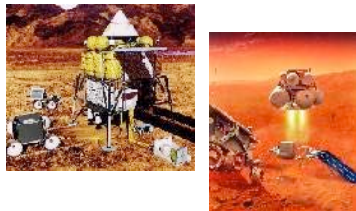
# Core ISRU Technologies Enable Multiple Applications



## Planetary Resource Utilization Maximizes Benefits, Flexibility, & Affordability

- Modular hardware & common mission fluids reduced logistics, increases reliability & flexibility, and reduces development and mission costs

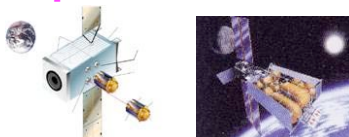
### In-Situ Production Of Consumables for Propulsion, Power, & ECLSS



### Fuel Cell Power for Spacecraft, Rovers & EVA



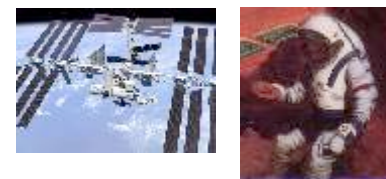
### 0-g & Reduced-g Propellant Transfer



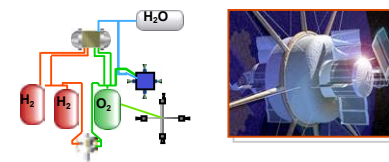
### Core Technologies

- CO<sub>2</sub> & N<sub>2</sub> Acquisition & Separation
- Sabatier Reactor
- RWGS Reactor
- CO<sub>2</sub> Electrolysis
- Methane Reforming
- H<sub>2</sub>O Separators
- H<sub>2</sub>O Electrolysis
- H<sub>2</sub>O Storage
- Heat Exchangers
- Liquid Vaporizers
- O<sub>2</sub> & Fuel Storage (0-g & reduced-g)
- O<sub>2</sub> Feed & Transfer Lines
- O<sub>2</sub>/Fuel Couplings
- Fuel Cells
- O<sub>2</sub>/Fuel Igniters & Thrusters

### Life Support Systems for Habitats & EVA



### Water – Gaseous H<sub>2</sub>/O<sub>2</sub> Based Propulsion



### Non-Toxic O<sub>2</sub>-Based Propulsion





# ***ISRU With & Without Mars Water***



## **Without Mars Water**

- Atmosphere provides carbon dioxide and buffer gases (nitrogen and argon)
- Carbon dioxide (CO<sub>2</sub>) can be split to produce oxygen
  - Oxygen alone is up to 70% of total propellant mass (fuel dependant)
  - Supports EVA and life support backup
  - Technologies are immature
- Hydrogen can be used to make fuel
  - Earth supplied hydrogen & Mars CO<sub>2</sub> can support >12:1 mass leverage of hydrogen brought vs propellant produced
    - Volume and power issues with hydrogen delivery to Mars
    - Similar technologies to life support systems
  - Water from fuel cell power production can be regenerated into oxygen and hydrocarbon fuel with Mars CO<sub>2</sub>

## **With Mars Water**

- Eliminates need to transport hydrogen from Earth
- Mars CO<sub>2</sub> and water enables:
  - Oxygen and wide range of fuel options (methane easiest to produce)
    - Hydrocarbon fuel lower power and easier to store than hydrogen
  - Plastic and petrochemical products; polyethylene radiation shielding
  - Cement-like construction materials
- Mars water provides backup to life support water and in-situ radiation shielding



# Objectives of Lunar ISRU Development & Incorporation

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- Identify and characterize resources on Moon, especially polar region
- Demonstrate ISRU concepts, technologies, & hardware that reduce the mass, cost, & risk of human Mars missions
  - Excavation & water extraction
  - Thermal/chemical processing subsystems
  - Cryogenic fluid storage & transfer
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables
  - Landing crew with pre-positioned return vehicle or 'empty' tanks
- Develop and evolve lunar ISRU capabilities that *enable* exploration capabilities
  - ex. Long-range surface mobility, global science access, power-rich distributed systems, enhanced radiation shielding, etc.
- Develop and evolve lunar ISRU capabilities to support sustained, economical human space transportation and presence on Moon
  - Lower Earth-to-Orbit launch needs
  - Enables reuse of transportation assets and single stage lander/ascent vehicles
  - Lower cost to government thru *government-commercial* space commercialization initiatives



# ***Objectives of Mars ISRU Development & Incorporation***

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- Utilize Earth-based and Lunar ISRU development and testing to maximum extent possible
- Utilize information from past, current, and planned Science missions to provide critical environment, resource, and design data when possible
- Perform measurements of global resources, local resources, and local environment - Combine with science missions where appropriate
- Perform ISRU demonstrations in step-wise approach to increase confidence in environment/resource understanding and reduce mission application uncertainties
  - Experiment development time, 26 month gaps in missions, trip times, and extended surface operations mean lessons learned from one mission can only influence missions 2 or 3 opportunities (4 or 6 years) later
  - Parallel investigations of atmospheric and regolith/water-based processing with convergence before human mission
- Utilize step/spiral development of identified ISRU Capabilities:
  - Mission consumable production
  - Water extraction & processing
  - Regolith processing for manufacturing of spare parts & other infrastructure items
  - Regolith manipulation and processing for construction (landing pads, radiation shielding, berms for nuclear reactor or plume debris mitigation, etc.)
  - Bio-plant growth support



# Brief Summary of Mars ISRU Technology Demos



## Focus Areas for Mars ISRU Development

- Atmospheric Collection & Processing
- Regolith/Water Collection & Processing
- In-situ Manufacturing/Construction
- In-situ Bio-Support & Plant Growth

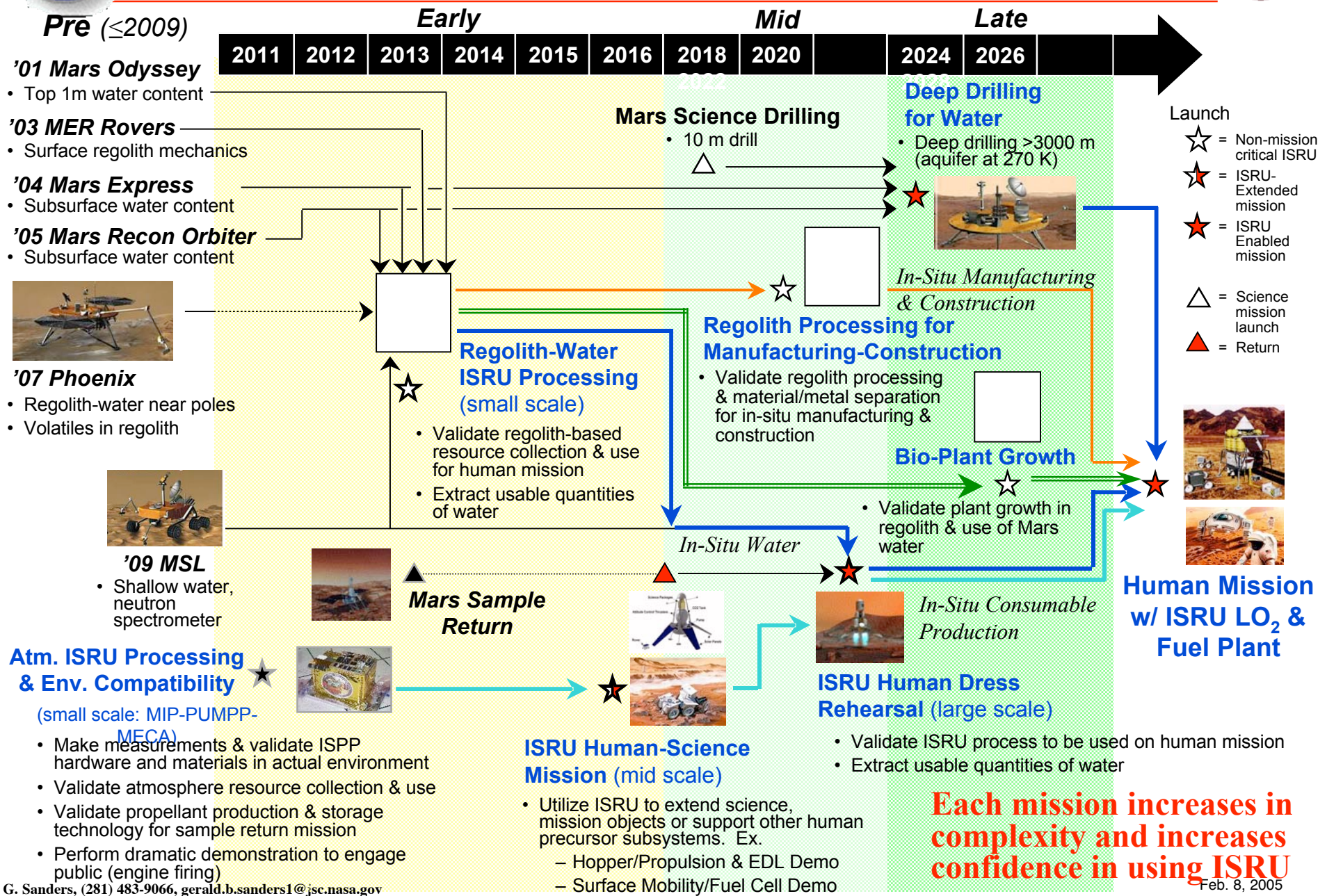
Primary  
Secondary

2011	- Small scale (1/200) atmosphere processing, including oxygen and methane production and storage.
2013	- Small scale, extract/purify water from top 2m of regolith; process/store oxygen and hydrogen.
2016	- Mid-scale (1/20) extended science or human precursor application mission.
2020	- Small scale regolith processing for manufacturing/construction purposes, if warranted by mass, risk, or cost.
2022	- Large scale (1/5) dress rehearsal of in-situ-enabled launch to at least Mars orbit.
2024	- Deep drilling to $\geq 3$ km if warranted by earlier search for water in 2013 and 2018 opportunities, or substitute a new ISRU demo based upon knowledge through about 2019.
2026	- Small scale bio-plant demo using water and regolith excavation/processing, if allowed based upon search for and knowledge of extant Martian life.

Mission also demonstrates capability for low rate production of oxygen for EVA and life support on future human Mars mission



# Mars ISRU Flight Demonstration & Mission Evolution





# ISRU Challenges



**Maximize benefit of using resources, in the shortest amount of time, while minimizing crew involvement and Earth delivered infrastructure**

- Early Mass, Cost, and/or Risk Reduction Benefits
  - Processing and manufacturing techniques capable of producing 100's to 1000's their own mass of product in their useful lifetimes, with reasonable quality.
  - Construction and erection techniques capable of producing complex structures from a variety of available materials.
  - In-situ manufacture of spare parts and equipment with the minimum of required equipment and crew training
  - Methods for energy efficient extracting oxygen and other consumables from lunar or Mars regolith
  - Methods for mass, power, and volume efficient delivery and storage of hydrogen
- Long-duration, autonomous operation
  - Autonomous control & failure recovery (No crew for maintenance; Non-continuous monitoring)
  - Long-duration operation (ex. 300 to 500 days on Mars surface for propellant production)



## ISRU Challenges (Cont.)



- High reliability and minimum (zero) maintenance
  - High reliability due to no (or minimal) maintenance capability for pre-deployed and robotic mission applications
  - Networking/processing strategies (idle redundancy vs over-production/degraded performance)
  - Development of highly reliable thermal/mechanical cycle units (valves, pumps, heat exchangers, etc.)
  - Development of highly reliable, autonomous calibration control hardware (sensors, flowmeters, etc.)
- Operation in severe environments
  - Efficient excavation of resources in extremely cold (ex. Lunar permanent shadows), dusty/abrasive, and/or micro-g environments (Asteroids, comets, Mars moons, etc.)
  - Methods to mitigate dust/filtration for Mars atmospheric processing
- Availability of Power
  - 1 to 4 KWe for 300 to 500 sols for Robotic ISRU mission such as sample return.
  - 30 to 40 KWe for human mission propellant production;
    - Less than power typically required for Environmental Control & Life Support System (ECLSS)
    - Single power system (nuclear reactor) can cover both ISRU & ECLSS needs if use is in series (i.e. ISRU before crew lands, ECLSS after crew lands)



## ***Next Steps: Recommendations***



### **ISRU, especially with Mars water, appears to be one of the enabling capabilities for human Mars exploration**

- Investigate Water availability on Mars
  - **Determining quantity and form of surface/sub-surface water is critical**
    - Maximum leverage if water is available on Mars (methane and oxygen)
    - Significant leverage even if water not available (oxygen only)
  - **Water location, accessibility, and processing requirements remain the big unknowns in ISRU planning**
    - The major uncertainty is in equatorial water deposits: distribution, depth, abundance, accessibility, process requirements - Precursor mission needed to clarify unknowns
- Incorporate & demonstrate ISRU hardware/systems in relevant environment in logical and orderly progression
  - Water resource measurement and extraction methods
  - Atmospheric processing for propellants & life support consumables
  - Surface material manipulation, excavation, & transport
- Maximize use of common technologies, hardware, and mission consumables between ISRU, propulsion, mobile power, life support, and EVA suit systems



## ***Next Steps & Recommendations (Cont.)***

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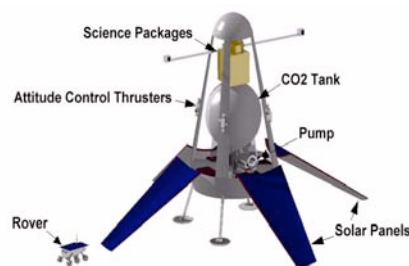
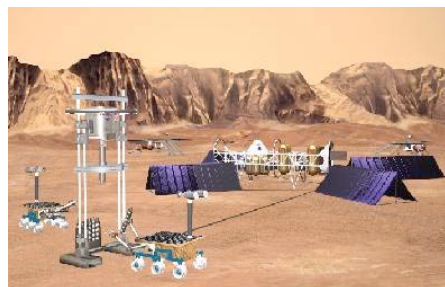
- Evaluate & promote mission concepts and architectures that maximize use & benefits of ISRU
  - Robotic precursors and pre-positioning
  - Maximize Delta-V of lander/ascent vehicles with in-situ propellants
  - Reuse of transportation elements
- Use Moon for operational experience and mission validation for Mars
  - Pre-deployment & activation of ISRU assets
  - Making and transferring mission consumables
  - Landing crew with pre-positioned return vehicle or 'empty' tanks
- Initiate development of Mars ISRU components and systems for robotic precursors
  - Recent NASA BAA selections is a good start, but primarily focused on lunar ISRU
  - Mission phasing and pass-back of lessons learned require start now.
  - Moderate funding required to advance individual component and subsystem technologies



# ***BACKUP CHARTS***



# Mars ISRU For Robotic/Human Exploration



## Critical Technology Needs / Opportunities

- Mars atmospheric CO<sub>2</sub> acquisition technology
- N<sub>2</sub>, Ar, & CO<sub>2</sub> separation
- CO<sub>2</sub> reduction to O<sub>2</sub> and CO
- H<sub>2</sub>O reduction to H<sub>2</sub> & O<sub>2</sub>
- CO/CO<sub>2</sub> conversion to methane & other hydrocarbons
- Methane reduction to H<sub>2</sub> and CO
- Surface cryogenic liquefaction, storage, & transfer
- Autonomous control, failure detection, isolation, & recovery

## Viable Time Frame

- Robotic Missions: 2007 to 2016
- Human Missions: 2018+

## Description & Approach

- Utilize Mars atmosphere and soil-based resources to produce mission critical consumables instead of bringing them from Earth to reduce Earth launch mass and cost, and reduce mission risk. Processes and mission critical consumables include:
  - Production of propellants for Mars ascent vehicles and hoppers
  - Production of fuel cell reagents for powering rovers, science instruments, deep drills, and aerobots
  - Production of O<sub>2</sub>, H<sub>2</sub>O, and buffer gases for life support backup and EVAs
  - Removal of permafrost/water from regolith for life support and consumable production
- Develop common technologies for propellant & fuel cell reagent production, life support and EVA systems, and fuel cell power generation to minimize cost and risk, including reactors, H<sub>2</sub>O/CO<sub>2</sub> electrolysis, and gas/gas, gas/liquid separators and dryers

## Major Sub-system Elements / Metrics

- Mars CO<sub>2</sub> acquisition system: Robotic <12 kg/sol, Human <200 kg/sol
- Propellant production system: Robotic 0.5 kg/hr - 8 hrs, Human 4 kg/hr - 24 hrs
- Water production: Human 1.2 kg/hr-24 hrs
- Buffer gas production: Robotic 10 to 100 gms/sol: Human .75 kg/hr
- Rover fuel cell reagents: Robotic 0.3 kg/sol: Human 10 kg/hr-24 hr

## Mission Applications/ Benefits

- Exploration
  - Robotic: sample return, hoppers, rovers, science instruments - Benefits: reduces mass & extends mission
  - Human - EVA & Life support, propellants for hoppers & ascent - Benefits: reduced mass & risk
- Commercial Space
  - Earth-spinoff for automotive fuel cell & fuel production

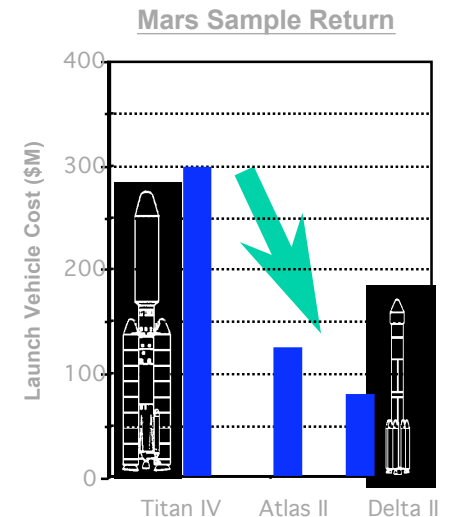


# ISRU vs. Non-ISRU Mars Mission Study Results



## Mars Sample Return with & without ISRU (Multiple Studies)

- **20% to 35% reduction** in launch **mass** for Mars Sample Return
- Possible use of Delta II or Atlas II versus Titan IV or Proton **reduces launch cost** by a **factor of 2 to 3**
- ISRU **enables** Direct Earth return sample return mission with large sample (5+ kg)
- Propellant production unit for Mars sample return mission is:
  - Same scale of production unit to supply EVA oxygen or EVA fuel cell powered rover
  - Scalable to human mission propellant production package

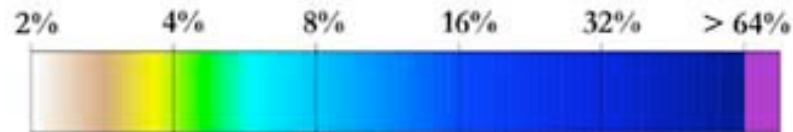


## Human Mars Missions

- **21 to 25% mass reduction** for Human Mars Design Reference Mission
  - Smaller lander = smaller Mars trans stage and Mars orbit capture vehicles
  - Greater mass savings with increasing Delta-V (i.e. higher Mars rendezvous orbit)
- **3.5:1 mass savings leverage** from Mars surface back to Earth, i.e. 30 MT of in-situ propellant production equals >100 MT in Low Earth Orbit



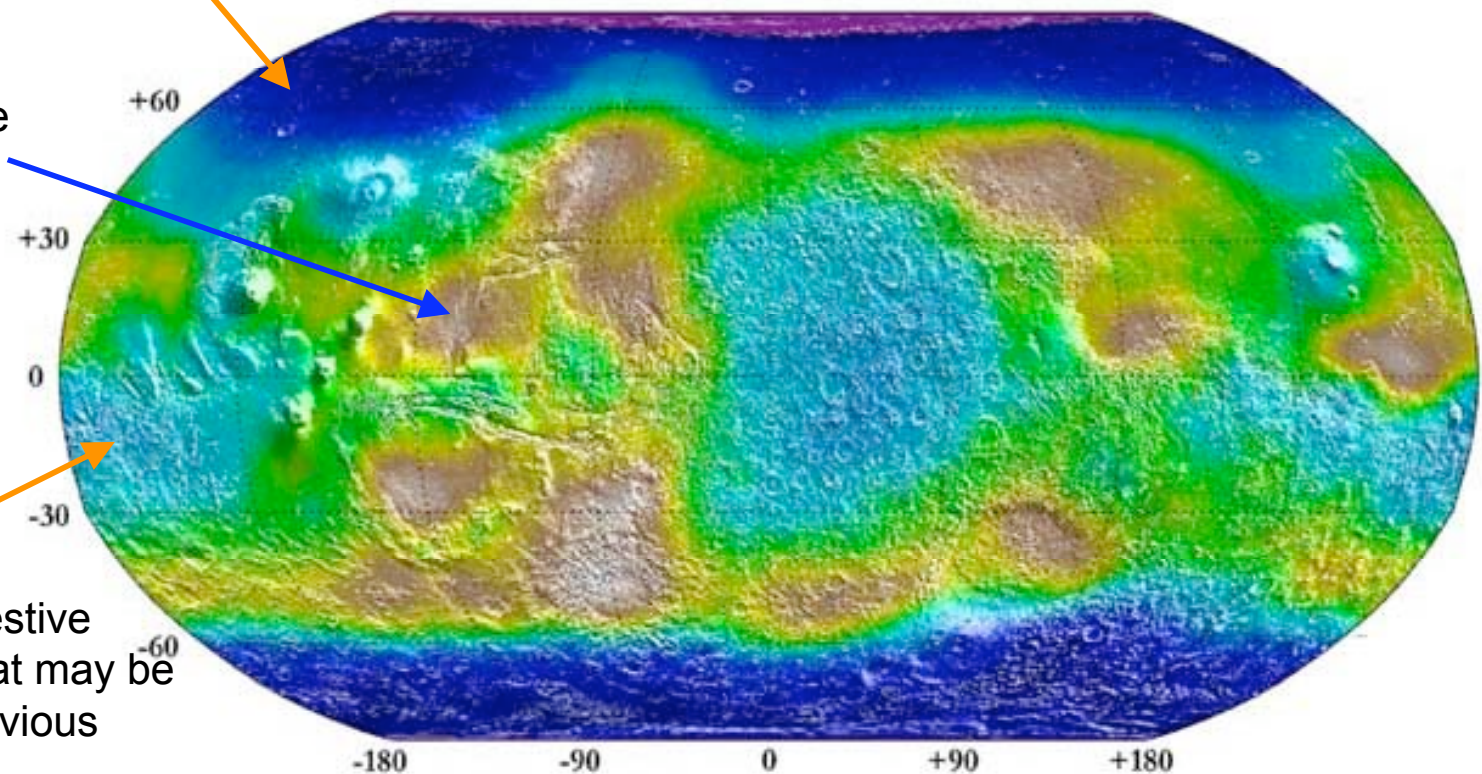
# Water Distribution in top ~ 1 m of Mars



Dark blue areas are almost surely ice-filled pores

Low H<sub>2</sub>O areas are likely to be bound water in minerals

Light blue areas are regions of high albedo and low thermal inertia suggestive of subsurface ice, that may be left over from the previous Mars ice age





# Overview of Water on Mars



## ▪ Equatorial Region ( $\pm 30^\circ$ )

- Viking measured 1 to 3% water by mass
- Mars Odyssey data suggests three specific regions with up to 8-10% water by mass in the top 1 m
  - Analysis of fast and slow neutron data indicates this water is buried beneath at least 30 cm of dry regolith, suggesting that it might be buried ice left over from a previous Mars ice age
  - Additional evidence is the close conformity of these 3 regions to regions of low thermal inertia and high albedo (i.e. cold subsurfaces)

## ▪ Mid Latitude ( $40^\circ$ to $55^\circ$ )

- Subsurface ice table may be within top few meters in some localities with low thermal inertia (uncertain)

## ▪ High Latitude ( $55^\circ$ - $70^\circ$ )

- Near-surface subsurface ice tables are widely prevalent (strong evidence)

## ▪ Polar Regions ( $+70^\circ$ )

- Mars Odyssey data suggests >50% water ice by mass at or near surface
  - Phoenix will provide vital data
- Frozen  $\text{CO}_2$  also present as other concentrated resource at south pole

## ▪ Deep Aquifers

- Subsurface thermal gradient predicts  $T > 273 \text{ K}$  at depths several kilometers below surface ( $>3000 \text{ m}$ ) indicating that liquid aquifers might be possible
- Visual data from mid/upper-latitude sidewall gullies can be interpreted that liquid water may be present at 200 to 500 m below plateau top (C. Stoker & D. McKay)



# Current In-Situ Consumable Production Technical Approaches



## CO<sub>2</sub> Acquisition and Compression

### Passive Adsorption Pumps

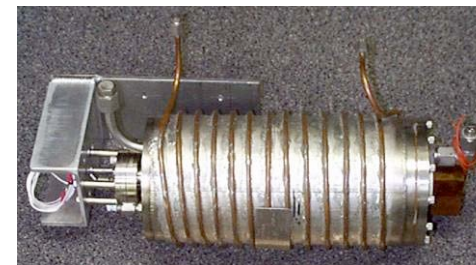
- Mars atmosphere enters adsorption bed in pump passively through diffusion process. Mars atmospheric CO<sub>2</sub> is preferentially adsorbed when the sorbent material is cold. CO<sub>2</sub> is desorbed by heating the sorbent material in an enclosed volume; CO<sub>2</sub> is thus pressurized.
- Several prototypes have been built and tested.

### Active Adsorption Pumps

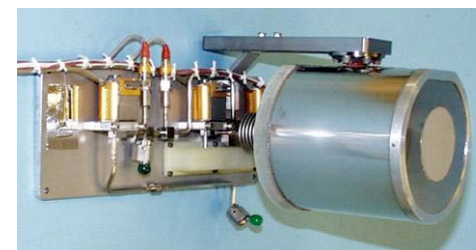
- The Mars atmosphere is actively moved through the adsorption beds using a fan or pump. This is required to obtain faster or larger amounts of CO<sub>2</sub> not possible with diffusion alone.

### CO<sub>2</sub> Solidification Pumps

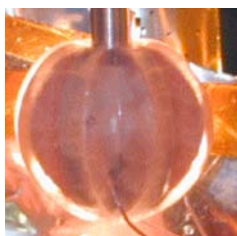
- CO<sub>2</sub> is acquired and separated from the Mars atmosphere through preferential solidification using an active cooling device. Once collected, the temperature and pressure in the solidification pump is allowed to rise until the CO<sub>2</sub> changes phase to a high pressure liquid.



LMA Adsorption Pump Breadboard



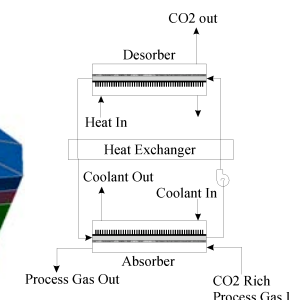
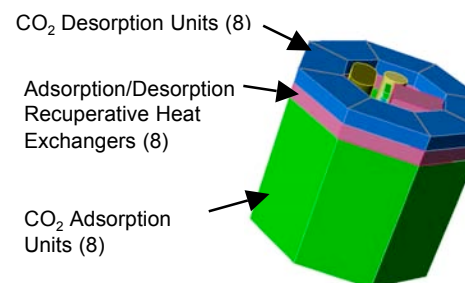
MAAC Flight Hardware built by JPL



LMA CO<sub>2</sub> Solidification Pump Heat Exchanger



Sorbent Pump Prototype built by NASA Ames



Microchannel Sorbent Pump Concept Under Development by PNNL



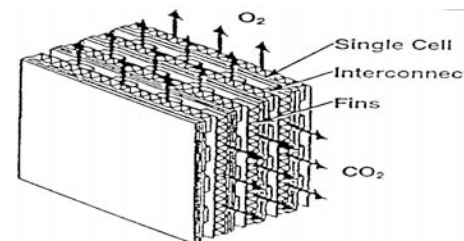
# Current In-Situ Consumable Production Technical Approaches (Cont.)



## Oxygen Generation by CO<sub>2</sub> Electrolysis

- Pressurized and heated CO<sub>2</sub> is passed over a hot electrolysis cell composed of a Yttria-stabilized zirconia (YSZ) solid electrolyte wafer sandwiched between Pt electrodes. Pure O<sub>2</sub> is produced at the anode.
- University of Arizona built a single-cell device for the Mars ISPP Precursor flight experiment package.
- Allied Signal built a multi-cell YSZ-based CO<sub>2</sub> electrolysis unit as a demonstration prototype.

Allied Signal  
Multi-cell  
YSZ-based  
Electrolysis Unit

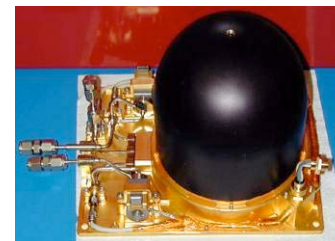


## RWGS & Alternate CO<sub>2</sub> Reduction

### Reverse Water Gas Shift (RWGS)

An initial source of H<sub>2</sub> from Earth is reacted with pressurized CO<sub>2</sub> in the RWGS reactor to produce H<sub>2</sub>O and CO. The H<sub>2</sub>O is condensed and electrolyzed to form H<sub>2</sub> and O<sub>2</sub>. The O<sub>2</sub> is collected as a propellant product (oxidant). The H<sub>2</sub> is re-circulated. RWGS breadboards have been tested by Pioneer Astronautics and KSC

OGS  
Prototype for  
MIP



RWGS  
Breadboard At  
KSC



### Alternate CO<sub>2</sub> Reduction

Possible alternate CO<sub>2</sub> reduction technologies:

- Electrolysis of CO<sub>2</sub> in Non-Aqueous Solvents
- Electrolysis of molten carbonates
- Molten salt electrolysis
- Room temperature ionic liquid electrolysis
- Liquid and super critical CO<sub>2</sub> electrolysis

Alternate CO<sub>2</sub>  
Reduction  
Characterization  
Breadboard At KSC





# Current In-Situ Consumable Production Technical Approaches (Cont.)



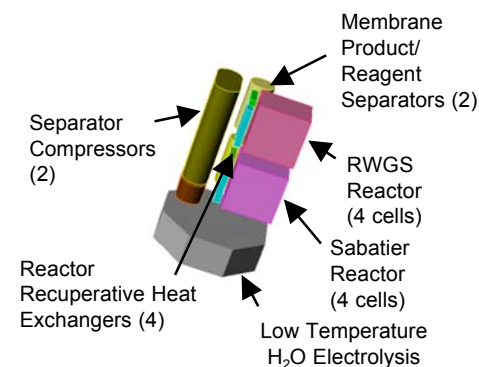
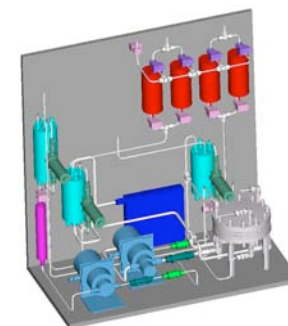
## Oxygen & Methane Production By Sabatier Reactor/Water Electrolysis (SR/WE)

- A source of hydrogen ( $H_2$ ) is needed either from Earth or from Mars. The  $H_2$  is reacted with pressurized  $CO_2$  in the Sabatier reactor to produce methane and water.  $CH_4$  is collected as a propellant product (fuel). The  $H_2O$  is electrolyzed to form  $H_2$  and  $O_2$ .  $O_2$  is collected as a propellant product (oxidant), and the  $H_2$  is recycled.
- 1<sup>st</sup> Generation SR/WE Breadboard
  - Produced 0.17 kg of  $O_2$  & 0.04 kg of  $CH_4$  per 8 hr day
- 2<sup>nd</sup> Generation SR/WE Breadboard
  - Produces 0.50 kg of  $O_2$  & 0.13 kg of  $CH_4$  per 8 hr day - Mars Orbit Rendezvous sample return mission scale
  - 50 to 75% reduction in breadboard mass, volume, and power
  - Initial design complete and subsystems built
- Microchannel Chemical/Thermal System (MCTS) Technology for SR/WE/RWGS
  - Joint NASA/JSC and DOE/ (PNNL) effort
  - In 1st year of 3 year effort
  - 3rd year will demonstrate integrated MCTS ISCP plant which will produce 3 kg of  $O_2$  & 0.8 kg of  $CH_4$  per 8 hr day - Direct Earth return Mars sample return mission scale

1<sup>st</sup> Gen SR/WE  
Breadboard



2<sup>nd</sup> Gen SR/WE  
Breadboard



Total External Size: 12 in dia., 10 in. high

**Microchannel SR/WE/RWGS Concept Under  
Development by PNNL**



# Mars ISCP Process Options



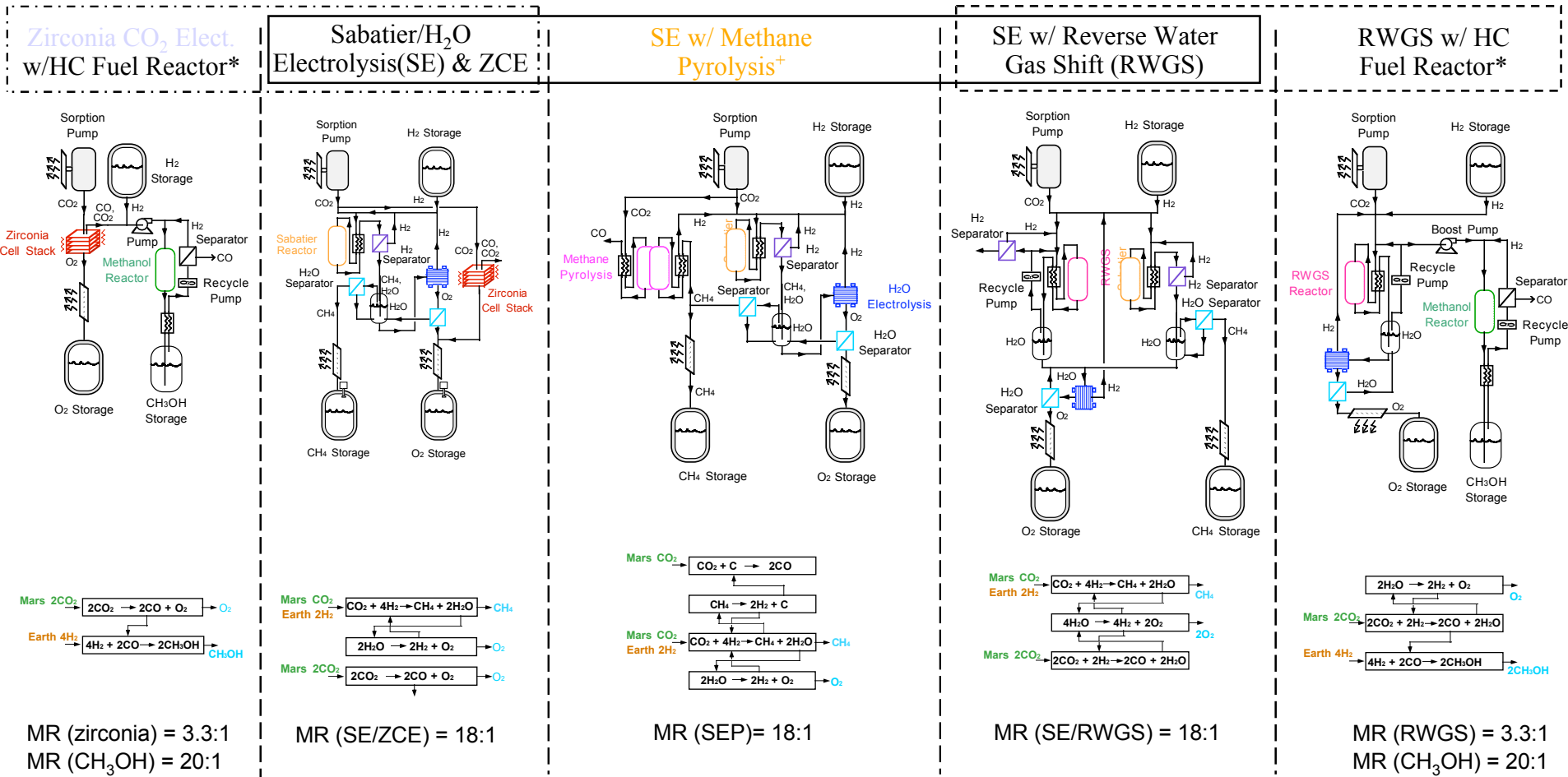
Process Option	Feedstock	Preferred
Oxygen (O <sub>2</sub> )/Hydrocarbon Fuel		
• Sabatier/Water Electrolysis (SE) and throw away methane to raise mixture ratio from 2:1 to 3.5:1	Hydrogen or H <sub>2</sub> O, CO <sub>2</sub>	
• SE w/ Reverse Water Gas Shift (RWGS) for extra O <sub>2</sub>	Hydrogen or H <sub>2</sub> O, CO <sub>2</sub>	
• SE w/ Methane Pyrolysis/Conversion for extra O <sub>2</sub> production	Hydrogen or H <sub>2</sub> O, CO <sub>2</sub>	X
• Zirconia cell w/ hydrocarbon reactor	Hydrogen or H <sub>2</sub> O, CO <sub>2</sub>	X
• RWGS w/ hydrocarbon reactor	Hydrogen or H <sub>2</sub> O, CO <sub>2</sub>	X
• Carbon dioxide (CO <sub>2</sub> )/Water Reactors	H <sub>2</sub> O, CO <sub>2</sub>	
O <sub>2</sub> /Earth Fuel or O <sub>2</sub> /Carbon Monoxide (CO)		
• SE w/ Full Methane Pyrolysis/Conversion	Hydrogen to start, CO <sub>2</sub>	
• Bosch/Water Electrolysis	Hydrogen to start, CO <sub>2</sub>	
• Zirconia Cell	CO <sub>2</sub>	X
• Silver glow/Radio-Frequency discharge	CO <sub>2</sub>	
• Reverse Water Gas Shift (RWGS)	CO <sub>2</sub>	
Carbon Dioxide (CO <sub>2</sub> )		
• CO <sub>2</sub> w/ Diborane (B <sub>2</sub> H <sub>6</sub> ) brought from Earth	CO <sub>2</sub>	
• CO <sub>2</sub> in Nuclear thermal reactor	CO <sub>2</sub>	

Preferred rating based on trade studies considering complexity, reliability, technology readiness, power required, and mass

**Note: Availability of assessable water on Mars would promote use of chemical processes that utilized water electrolysis**



# Primary Mars ISCP Options Under Consideration



$$\text{Mass Ratio (MR)} = \frac{\text{ISPP Product Mass}}{\text{Earth Fuel or Reagent Mass}}$$

Notes: \* Hydrocarbon Fuel (HC) options include methanol ethylene or other possible HC fuels of interest

+ Methane (CH<sub>4</sub>) Pyrolysis can be replaced with reactor to convert CH<sub>4</sub> to hydrogen (H<sub>2</sub>) using CO<sub>2</sub>



# ISCP Concepts Distinctions



## Three Major ISPP Concept Distinctions

- Consumables Produced
  - O<sub>2</sub> Only
  - O<sub>2</sub> & Fuel (Series or Parallel)
- Resource Needs
  - Earth supplied or resource H<sub>2</sub>
  - No H<sub>2</sub> required
- Intermediate Product
  - Water based
  - Non-water based

## Mars ISCP Concepts

	O <sub>2</sub> Only	O <sub>2</sub> & Fuel (Series)	O <sub>2</sub> & Fuel (Parallel)	Earth supplied or resource H <sub>2</sub>	H <sub>2</sub> recycled or no H <sub>2</sub> required	Water based	Non-water based
Zirconia CO <sub>2</sub> Electrolysis (ZCE)	X				X		X
Reverse Water Gas Shift (RWGS)	X				X	X	
Sabatier/Water Electrolysis (SWE) w/ full Methane Conversion	X				X	X	
ZCE w/ Hydrocarbon Fuel Production		X		X			X
SWE w/ ZCE			X	X		X	
SWE w/ partial Methane Conversion			X	X		X	
SWE w/ RWGS			X	X		X	
RWGS w/ Hydrocarbon Fuel Production		X		X		X	



# Mars ISCP Process Benefits/Challenges

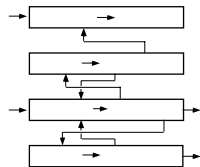
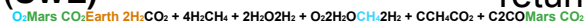


## Process option

## Benefits

## Weaknesses/Challenges

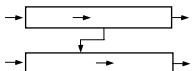
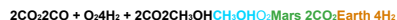
### Sabatier/Water Electrolysis (SWE)



- Both fuel and oxidizer created for return propulsion
- Sabatier/water electrolysis has high TRL based on ECLSS experience
- Sabatier & RWGS have similar architectures so integration possible
- Supports water-based ISRU

- Liquefaction of both  $\text{O}_2$  and  $\text{CH}_4$
- Regenerative product and water separation for  $\text{CH}_4$ ,  $\text{H}_2$ , and  $\text{O}_2$  gas streams
- Reliability for complex system for >500 day operation
- Requires in-situ water or third process to make propellants at proper mixture ratio

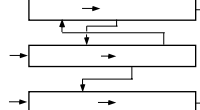
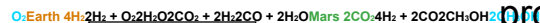
### Zirconia $\text{CO}_2$ Electrolysis (ZCE)



- Extremely simple & potentially highly reliable - Solid state
- Fuel production can be added in series
- Fuel produced does not require liquefaction
- Supports  $\text{O}_2/\text{CO}$  hopper and fuel cell rover with no earth logistics

- Development of a zirconia cell stack which is robust, efficient, and can undergo thermal cycling
- High thermal/electrical power requirements
- Can require 2 times  $\text{CO}_2$  needs

### Reverse Water Gas Shift (RWGS)



- Attractive if Zirconia Cell not possible
- Enhances sabatier/water electrolysis process by raising ox/fuel mixture ratio
- Fuel production can be added in series
- Fuel produced does not require liquefaction

- Currently at very low TRL (catalyst work required)
- Recirculation loop required
- High pressure processes
- Reliability for complex system for >500 day operation



# ISRU Enables Highly Capable, Affordable & Sustainable Surface Exploration Infrastructure



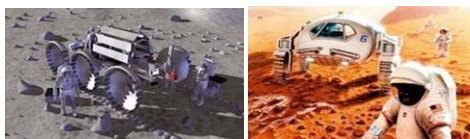
## Robotic Precursors & Tele-robotic Science



## EVA Astronaut w/ Robotic Assistant



## EVA w/ Pressurized or Un-Pressurized Rovers



## Crewed & Science Landers & Hoppers



### ***Power-rich environment enables new science, capabilities, and relaxed power constraints***

- Single main power source produces oxygen & fuel cell reactants for all surface assets (EVA suits, rovers, etc.)
- High power on demand capability
- Swap new fuel cell reactants w/ used water on return with samples



### ***Modular common hardware for reduced logistics, higher reliability, and increased flexibility & safety***

- Reduced logistics needs
- Simplified spare parts manufacturing or scavenging possible



### ***Production of common mission consumables increases mission effectiveness, sustainability, & provides functional redundancy to minimize risk***

- Resupply EVA O<sub>2</sub> & FC reactants from Rover to extend EVA or in case of emergency



### ***Infrastructure is reusable and easily expandable from simple robotic lander to full human presence***

- More assets can be added with increase in production capability
- Increased surface access possible with ISRU
- ISRU hoppers enable surface access at fraction of cost of dedicated lander mission
- MAV size reduced if lander stage is reused with in-situ propellant



# Surface Infrastructure Based On Common Supplied Fluid

ISRU-



***A small ISRU plant can support Life Support, EVA, Rover, or Mars ISRU Sample Return Missions***

## In-Situ Production Of Consumables



Production Rate:

MISR: 0.1-0.4 kg of O<sub>2</sub>/hr – 8 hrs

Human Mars: 2-4 kg of O<sub>2</sub>/hr – 24 hr

## Non-Toxic O<sub>2</sub>-Based Propulsion

Mars ISRU Sample Return      Human Ascent Propulsion



Usage Rate:  
1500-3000 kg O<sub>2</sub>

Usage Rate:  
20,000 kg O<sub>2</sub>

Oxygen (O<sub>2</sub>)      Nitrogen (N<sub>2</sub>)

**Production,  
Storage & Use of  
Common Fluids  
Minimizes Risk &  
Cost**

Water (H<sub>2</sub>O)      Fuel (H<sub>2</sub>, CH<sub>4</sub>, etc.)

## Life Support Systems for Habitats & EVA

Habitat ECLSS



Usage Rate:  
0.4 kg of O<sub>2</sub>/hr  
(crew 6)

EVA ECLSS



Usage Rate:  
0.2 kg of O<sub>2</sub>/hr  
(crew 2)

## Fuel Cell Power for Rovers & EVA

EVA Rover (600 W)



Usage Rate:  
0.5 kg of O<sub>2</sub>/hr

EVA Suit  
(50-100 W)



Usage Rate:  
<0.08 kg of O<sub>2</sub>/hr

Human Rover (10 KW)



Usage Rate:  
9.4 kg of O<sub>2</sub>/hr



# ISRU Processes Affected by Mars Environment & Resource Characteristics



Mission Environment	ISRU Process	Potential Impacts/Effects
Surface fine & bulk regolith properties	Excavation	Impact: Could reduce efficiency of regolith excavation due to: <ul style="list-style-type: none"> <li>• Adhesion of particles/grain</li> <li>• Compactness</li> </ul>
	Regolith processing inlet/outlet	Impact: Could cause sealing problems for multiple cycle processing systems
Dust/dust storm Uncertainties <ul style="list-style-type: none"> <li>• Particle size distribution</li> <li>• Local dust amounts</li> <li>• Dust particle deposition rate (also gravity dependent)</li> </ul>	Filter design	Impact: reduced CO <sub>2</sub> acquisition or ISPP performance reduction due to contaminants <ul style="list-style-type: none"> <li>• Micron size level required for dust unknown due to lack of information</li> <li>• Delta -P/flow rate into sorption bed impacted</li> <li>• Dust holding capacity (regenerate or replace)</li> </ul>
	Radiators & thermal control	Impact: Insufficient heat rejection or increased thermal power demands at night <ul style="list-style-type: none"> <li>• Surface emissivity changes</li> <li>• Heat transfer coefficient change due to particles in the atmosphere</li> <li>• Radiation to space at night (sky sink temperature not known)</li> </ul>
	Solar power	Impact: Insufficient power or oversized array to handle degradation over time <ul style="list-style-type: none"> <li>• Surface dust coating and abrasion reduces cell efficiency</li> <li>• Temperature cycles and UV radiation degrade cell efficiency</li> <li>• Structure &amp; deployment mechanism needed to withstand wind loads</li> </ul>
	Control Electronics	<ul style="list-style-type: none"> <li>• Arcing, grounding, and electrostatic discharge</li> </ul>
Mars gravity (3/8 Earth -g)	Heat pipes	<ul style="list-style-type: none"> <li>• Thermal convection coefficient impact (see Radiators &amp; thermal control)</li> </ul>
	Water/gas separation	<ul style="list-style-type: none"> <li>• Separation system sizing impact if based on gravity</li> </ul>
	Cryogenic storage and distribution	Impact: Increased power demand <ul style="list-style-type: none"> <li>• Heat convection coefficient impact; surface tension/gravity influences</li> </ul>
Solar and atmospheric condition variations due to: <ul style="list-style-type: none"> <li>• landing site elevation</li> <li>• annual pressure/temperature cycle</li> <li>• day/night cycles</li> </ul>	Sorption compressor/collector	<ul style="list-style-type: none"> <li>• Sorption bed or mechanical unit must be sized to CO<sub>2</sub> partial pressure</li> </ul>
	Solar power	<ul style="list-style-type: none"> <li>• Temperature cycles and UV radiation degrade cell efficiency</li> </ul>
	Radiator/thermal control system	<ul style="list-style-type: none"> <li>• Radiator/thermal control system must be sized to surface and sky temperatures and solar flux</li> </ul>
	Chemical processes	<ul style="list-style-type: none"> <li>• Cooling may cause higher concentrations of gas impurities (N<sub>2</sub>, Ar, etc.) which may "poison" reactors</li> <li>• Dust poisoning of catalysts and electro-chemical/thermal reactors</li> </ul>
Near surface volatiles (composition/distribution)	Surface preparation for landers & habitats	<ul style="list-style-type: none"> <li>• Differential settlement, thermal decomposition of volatiles, and frost heave could effect lander mission success</li> </ul>



# Roadmap for Evolutionary ISRU Campaign



## Capabilities

### Resource Assessment

- Remote & Local Sensors
- Simulants

### In-Situ Resource Excavation & Separation

- Regolith Excavation
- Thermal/Microwave Extraction
- H<sub>2</sub>O Separation
- CO<sub>2</sub> & N<sub>2</sub> Separation

### Resource Processing

- Regolith Reduction for O<sub>2</sub> & Feedstock
- CO<sub>2</sub> Reduction
- H<sub>2</sub>O Reduction
- Fuel Production

### Consumable Storage & Distribution

- Cryocoolers
- Light Weight Tanks
- Disconnects/pumps
- Transfer/Distribution

### In-Situ Manufacturing

- Solar cell production
- Metallic part fab
- Polymer part fab.
- Ceramic part fab.
- Manufacturing NDE
- Metrology Processes

## Initial

## Mid-Term

## Long-Term

